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STRUCTURAL SUCCESS OR FAILURE?

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STRUCTURAL SUCCESS OR FAILURE?

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SYNOPSIS

A few typical examples of structural distress are described with the cause and correction generally described. Avoidance of such troubles is rather simple and inexpensive, correction is usually complicated, time consuming and costly in both money and reputation. Valuable lessons can be learned from impartial description of structural failures, not only the few spectacular collapses but also from the many "incidents" of non-conformity with expected action.

Compilation of such data is a necessary phase of the obligations of technical societies to their membership and should be undertaken as a service both to its membership and to the public as a professional duty. The gap between success and failure is often a very fine revision in detail; recognition of the necessary revision is the goal of this paper.

If we define structural failure as observed collapse, there are few failures. On the other hand, if non-conformity with design expectations is structural failure and if one takes the trouble to measure the shape and position of completed structures, there are many failures. This is more true in the complicated framings than in simple spans and pin connected trusses. Unwanted settlements, sometimes unexplainable deformations, are often found and it is questioned whether they are failures, or normal (but unexpected) strains or merely "incidents," using a foreign term to describe such conditions. Whether failure or not, there usually follows a long and expensive litigation where the experts are pumped by their clients' lawyers and cross-examined by the opponents in an attempt to pin down the "proximate" cause of the failure or incident. As if the legal fiction of one and only one cause can be determined by either observation or deduction. Sometimes there is a single explanation for a failure, usually it is a combination of conditions, mistakes, even dishonest performance but not a single item by itself can be picked as the sole and only cause of failure. Yet, each in a way is what may be the responsible straw that broke the camel's back.

Let us look at a few examples of structural failure and the possible causes. Exact identification of the projects is not given so as to avoid harm or hurt to people involved. As a preliminary item, there is the case of a retaining wall which certainly would have failed if I had not stopped in to see the work in progress. It was a standard design cantilever stem reinforced by vertical bars on the filled side. Part of an apartment house development in the suburbs, the wall was being built by the foundation subcontractor. The forms and steel were being erected and I saw that the bars were being set in the front face of the wall and not as shown on the plans. The foreman gave me a reasonable but wrong explanation by his off side remark that he didn't want to bother the architect or the engineer, but the plan was wrong and he made

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the fix personally. You see, he said, the bars belong on the outside because the earth holds one face and you need something to hold the other face of the wall. The rods were changed and new dowels put into the footing and the wall is still standing (it is now some 25 years old) but if it had failed could one blame only the foreman? What about lack of supervision, inspection, control and explanation. Structural design must be tied in as a simple package, with control of performance as well as of planning.

Another retaining wall case, this one a serious failure resulting in loss of life and therefore coming under criminal investigation, was a good and proper structural design, but a poor drafting job resulted in someone orderine one-quarter inch rods where 1 1/4 inch was intended. The "one" of the 1 1/4 had been placed directly over a vertical dimension line and as the tracing was used for making prints some of the pencil carbon wore off and later prints could easily be mis-read. (Fig. 1) Investigation disclosed that the design had been checked by an independent consultant for the village inspector before a building permit was issued, but no one on the job objected to the use of the hairpin wires, although the construction superintendent, the reinforcing detailer, and the foreman placing the steel all admitted questioning the light steel, but no one was on the job to see that the designer's intent was carried out, and apparently no one checked the reinforcing orders or the details, both of which showed the wrong steel.

Failures do occur in timber structures, in steel structures and in concrete structures. Publicity is kept to a minimum, as a result of which, lessons are lost. Even where collapse of a structure makes newspaper headlines with pictures and considerable published mis-information, the report of causes and reasons comes so late that no one is interested except the immediate family, and they do not feel like talking. Some years ago, a complete collapse of a building affected so many financial interests that it was necessary to determine the real causes. Under our direction, the wreckage was taken apart floor by floor, and the contents of each floor weighed and the construction carefully inspected. Fortunately the failure occurred after all employees had gone home, and eventually the fact that there were no fatalities so impressed the various interested parties that each one took a share of the loss by agreement without litigation. The photographs of the collapse of which only two are included, Figs. 2 and 3, indicate a definite axis of the funnel of failure. This axis was traced down floor by floor and actually pointed to a structural weakness which was probably the cause. The building had been used as a part of a large department store, built about 1870, with open light wells in the center area of each section. Sometimes, as many of you may remember, these walls were covered by glass panels. When the building was converted to commercial use, some one removed the panels and completed the wood flooring without changing or adding to the beam supports. On the first floor, there was found a paper cutting machine partly resting on the added flooring supported on 2 x 4's to fill in the old light well with a load of paper delivered on the day of the collapse surrounding the machine. The floor just couldn't take the concentration and sagged downward carrying everything down with it.

In 1940 at the Purdue University conference on Soil Mechanics, I showed some sketches to explain sudden changes in bracing reactions in trench sheeting. The same explanation is applicable to several types of structural failure where unexpected loads and reactions occur and so it is here repeated. A rigid timber carried by four men who have located themselves so as to support equal loads is being carried along a smooth surface (Fig. 4). When

man A steps into a depression, man B is overloaded and may collapse, throwing load back to A and some additional load to C with possible uplift on D. It is a simple qualitative description of how the reactions of a continuous structure are sensitive to displacement of the supports. It is the explanation of many types of structural failures.

An interesting and successful repair project handled a few years ago was the reconstruction of the structural steel frame of a 12 story office building where two interior columns suddenly dropped some 12 inches at 8 A.M. on a cold Saturday morning. Only the watchman was around and he first noticed that the roof water tank was broken and the water ran through the building washing papers into the street. Inspection of the column bases showed that 24" in beam grillages under two columns had collapsed and squeezed down 12". Careful mathematical analysis of the frame as a continuous structure indicated that the maximum loads which could come to these columns, if all foundations were equally stable—were not enough to overload the columns or the grillages. The materials existing on each floor were measured and weighed to determine actual live load, which was found to average 60 pounds per square foot, far below the rated permissive loading. The only source of load sufficient to crush the grillages was the exterior wall and exposures indicated new movements at foundation level. The section (Fig. 5) shows how neighboring excavation and dewatering caused temporary release of the foundation support under the exterior wall, transfer of the load to the next interior line of supports and collapse from overloading. Fig. 6 The collapse readjusted conditions to force the outside footing to take load again. Reconstruction procedure was rather simple. After shoring the floors at the failure areas, new grillage beams were placed of reduced depth to fit the space between the continuous pile cap and the column base, and each floor was jacked back to level with steel fillers set to close the gaps between the bottom of the floor girders and the column brackets reused as girder supports.

A more recent well publicized collapse of a concrete structure was also diagnosed on the basis of photographs which showed a funnel of failure pointing to an interior column as the axis of first movement. (Figs. 7 and 8) Later investigation showed that this column in the bottom story was tipped toward the exterior wall and the foundation conditions under the exterior wall columns were not the sound rock called for on the design plans. Transfer of load, in this case the weight of the concrete only, caused overstress at foundation level, tipping and loss of support in the flat slab floors. The slab could not span 54 feet, after one support became inoperative, and so collapse resulted. Investigation showed several discrepancies between design assumptions and actual performance, in addition to the foundations, and the structure was almost completely demolished before reconstruction. Lack of control and inspection has cost everyone concerned tremendous sums of money, not to mention the loss of three lives and injury to other workmen.

There have been at least four reported collapses of formwork supports in the past ten years, all of which were of similar cause. Concrete form supports do not get equally distributed load until all the concrete is in place. As the concrete filling progresses, the reactions vary and where the timbers are continuous there is a possible uplift at form supports beyond the concrete placing. If the timber falsework is not completely bolted or spiked together, supporting posts will come loose and fall when loaded. This is especially true when the falsework is high and the posts are in two lengths separated by a continuous intermediate sill member not bolted to both the lower and upper post sections.

Torsional strains are the frequent cause of local failures, cracks in spandrel facings, displacement of brick surfaces, and even encroachment on shaft openings. After a stair contractor complained that the shaft in a school building was encroached by the bottom flanges of the steel beams, exposure showed that the tops of the beams were out of level by 3/4" and the beams had twisted in their connections, the bottom flanges being as much as two inches out of position. To definitely prove that the condition was the result of construction methods, a typical steel framing panel was set up in the yard and the concrete man hung forms in the usual way. Telltale rods were connected vertically to the top flanges of the beams and as the concrete was placed, rotation of the beams was evident. The forms were hung by one sided wires to permit easy stripping. The load of the concrete caused torsional rotation of the beams and when the concrete hardened the beams remained in a distorted position. This is a common error in supported formwork, the hangers should be either on both sides of the beam or alternately placed, if the steel beams are to remain in a vertical position.

Torsion also occurs in concrete designs. Some 30 years ago when flat slab design standards required rather deep spandrel beams, diagonal cracks in the exterior faces of the spandrel and horizontal cracks in the exterior columns just below floor levels were investigated analytically. The amount of added reinforcing needed to keep such strains within desired limit was not economical and the writer advised that shallow spandrels be used with continuous hoops extended into the slab as top reinforcement to add torsional rigidity with reduced dimension of the strains. Recent examples of excessive deflection in long exterior spans are tied in with the failure to consider torsion deformations of the exterior spandrels.

Temperature expansion is another physical factor often overlooked. Long span trusses and girders in closed attic spaces will expand enough to push masonry walls out of position, when the attic space is heated. Rigid tile roof covering, not isolated from the parapet wall, will expand enough to push the wall off the supporting beams, when sun exposure builds up high temperature in the tile.

Well known pressures, such as the atmospheric pressure and hydrostatic pressure will cause failure if permitted to act where sufficient resistance is not provided. Steel rectangular tanks for fuel oil storage failed completely during a very cold day, when the evaporation of steam from the heated oil had frozen up the air relief pipes and oil was being withdrawn from storage with no available opening for air replacement. (Fig. 9) Concrete basement walls backfilled with clay which shrinks away from the concrete as it dries, leaves a narrow but continuous gap into which storm water flows easily and imposes full hydrostatic pressure. Figures 10 and 11 show the result of such conditions.

These are only a few of the types and causes of structural failure and the subject of foundations and mis-behaving piles has not been included in this paper.

The literature on structural failures is very scant, especially in this country. Somewhat more prominence is given in other countries to the lessons to be learned from non-successful designs. In Belgium, the Bureau Seco under the guidance of Magnel, controls designs and construction methods to prevent "incidents" and also to determine the causes of "incidents." The State of Sao Paulo in Brazil has a governmental department to make full investigation and public report on structural failures. In recent years, at the meetings covering foundation and soil mechanics the subject of failure is no longer

tabu. In 1952, Henry Loissier of France published a book on the Pathology of Reinforced Concrete, a study of failures, their causes and methods of correction.

In closing, the writer suggests the formation of a joint committee of the Structural and Construction Divisions to act as an investigating medium of all structural "incidents" not consistent with the expectations of recognized design procedures, with the duty to make public reports of their findings so that all may learn the lessons of the small insufficiencies which may separate failure from success.

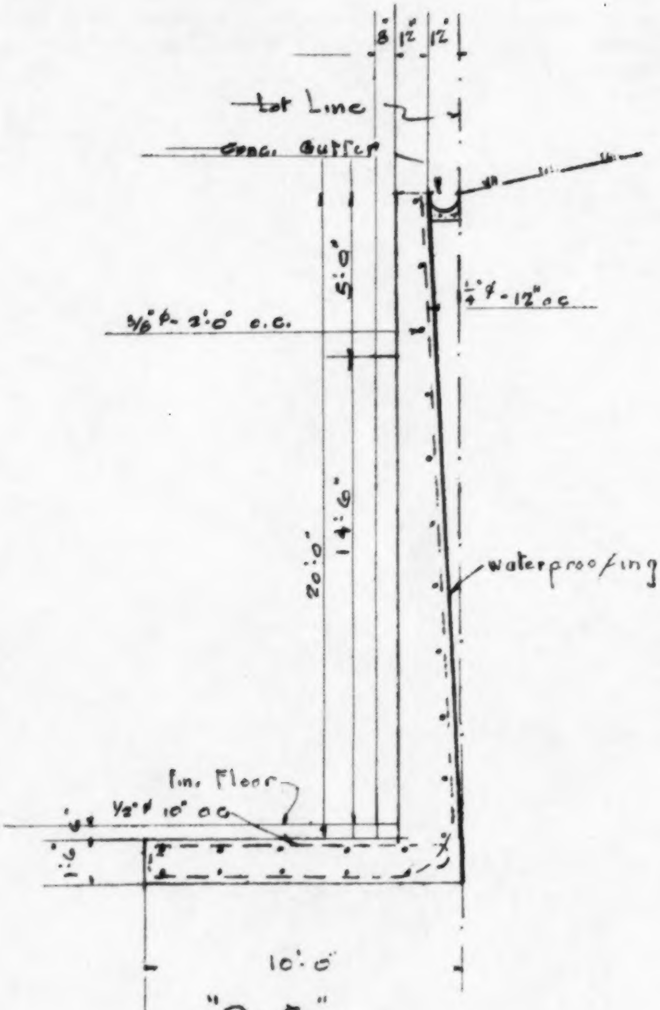

Fig. 1. Retaining wall section.

FROM 4TH FL.

Fig. 2. Funnel of collapse.

Fig. 3. Funnel of collapse.

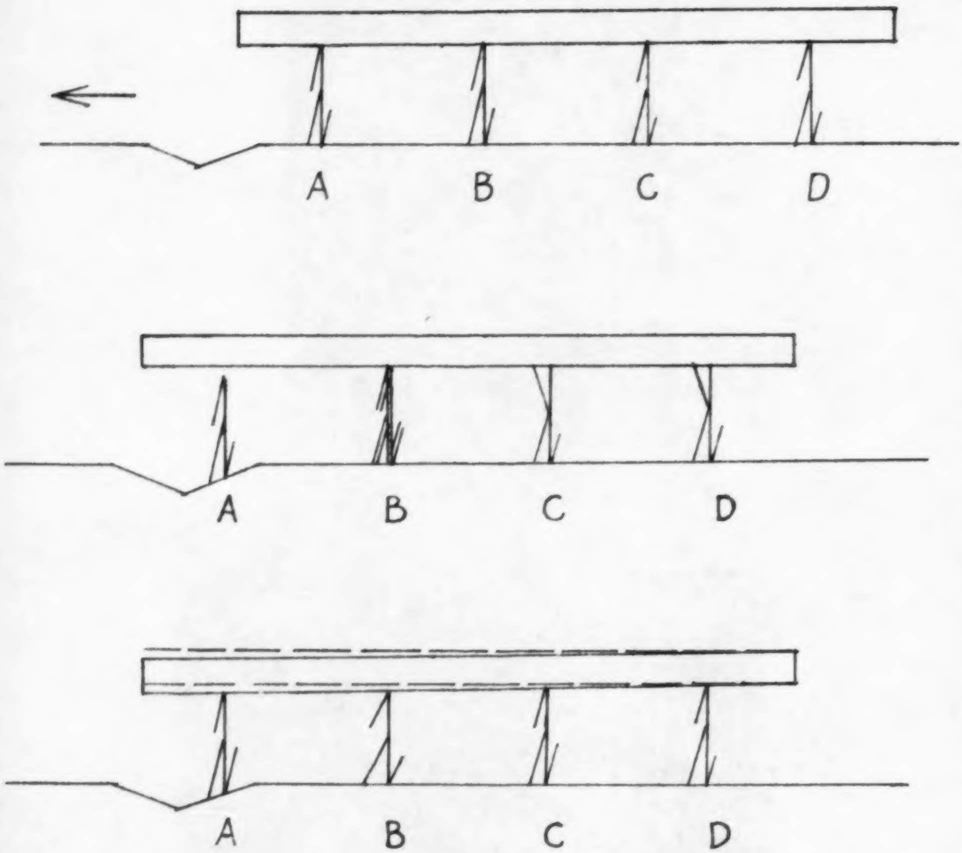

Fig. 4. Load transfer from settlement of support of rigid structure.

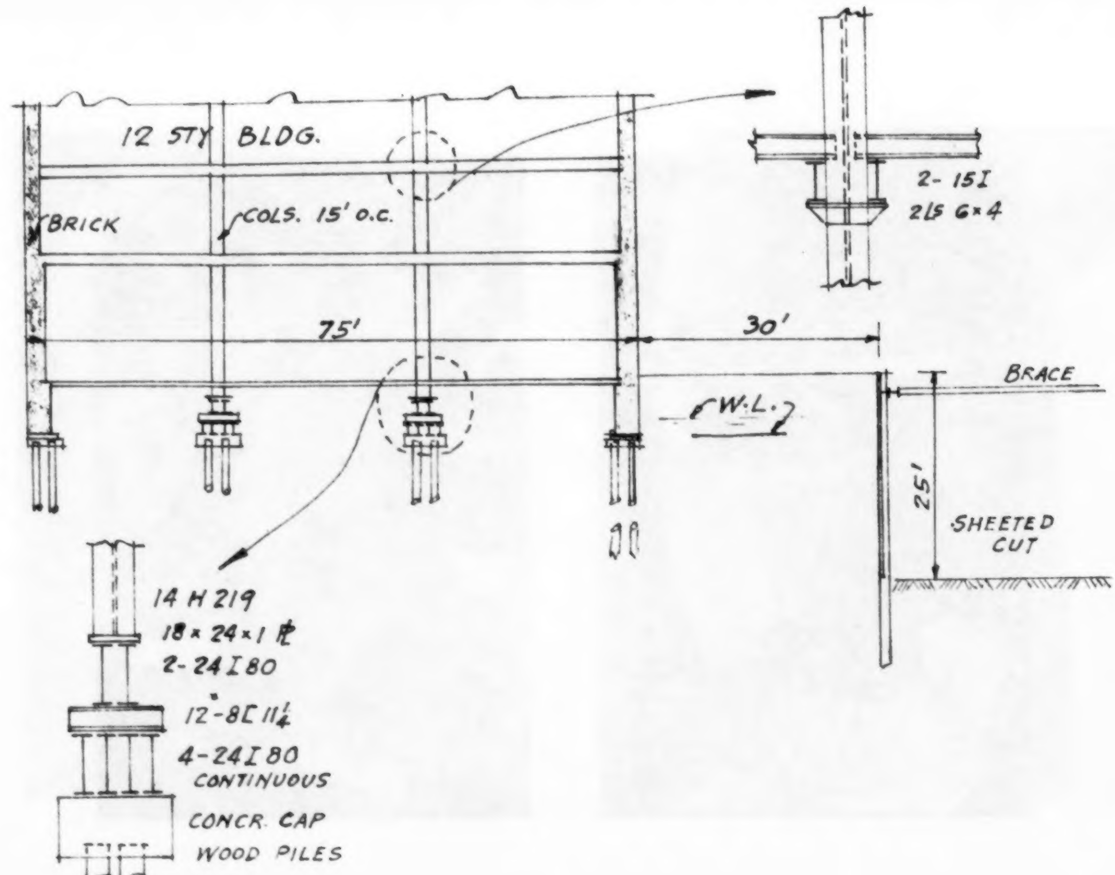

Fig. 5. Section of 12 sty. building with grillage detail.

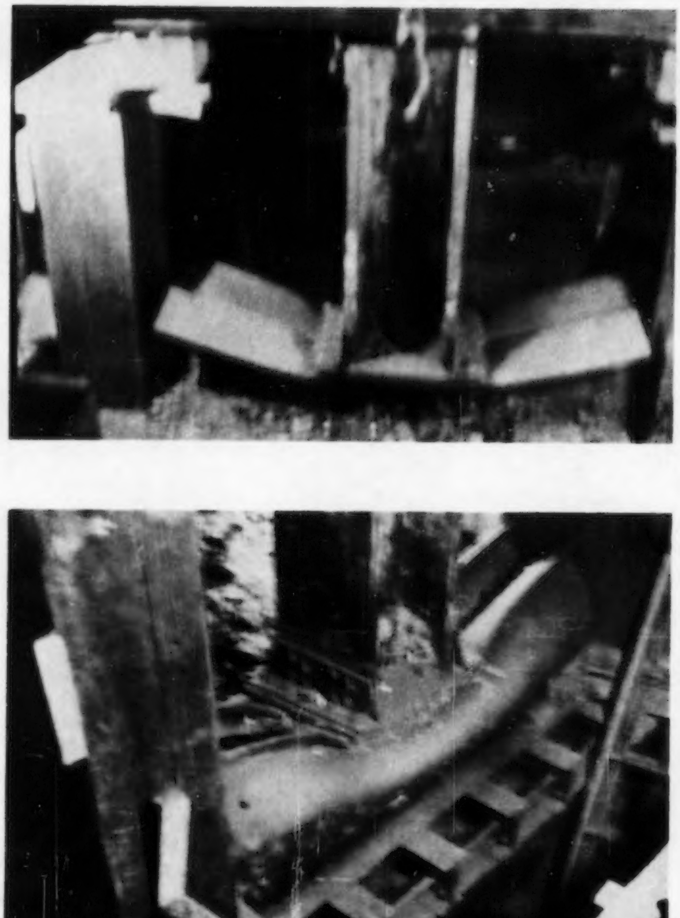

Fig. 6. Collapsed grillages.

Fig. 7. Collapsed concrete structure.

Fig. 8. Limit of collapse.

Fig. 9. Collapsed steel tank by air pressure.

Fig. 10.

Fig. 11. Walls collapsed by water pressure.